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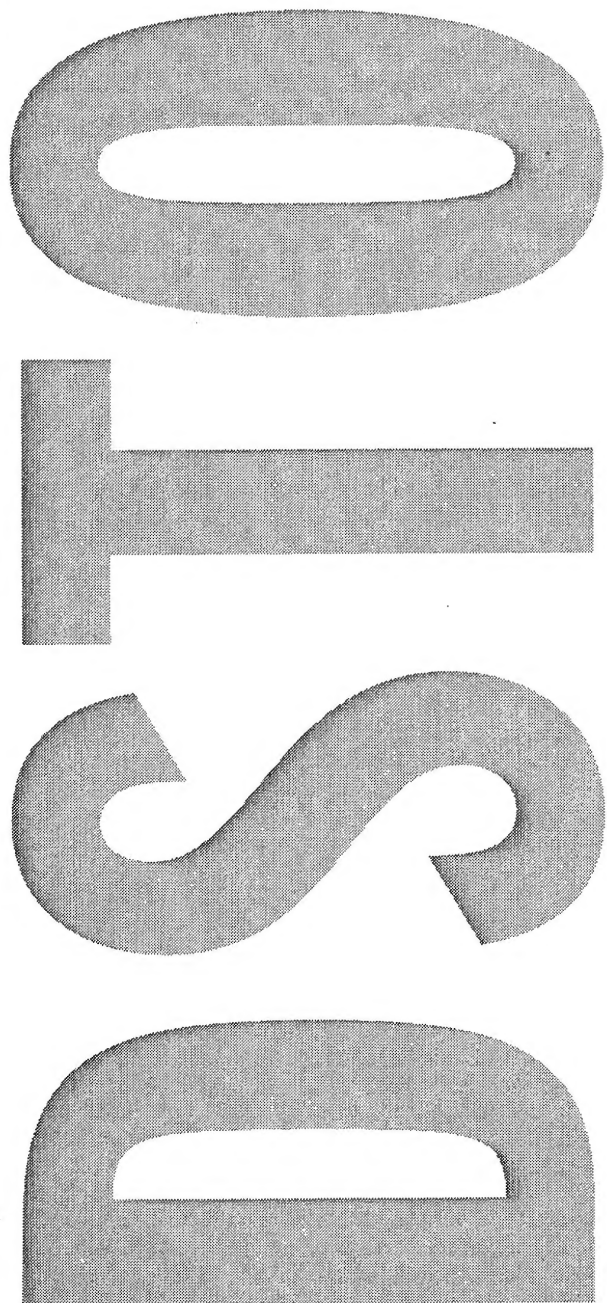Jul 2003

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The Effect of Water Mist and Water Spray on Radiative Heat Transfer for Stored Ordnance

Con Doolan

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Weapons Systems Division
Defence Science and Technology Organisation

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ABSTRACT

A method for determining the mitigating effects of water sprays and mists on thermal radiation is presented. The aim of the method is to provide a quantitative measure of the effectiveness of water sprays with various droplet radii at mitigating thermal radiation and apply the results to ordnance stored in magazines. A water droplet Mie-scattering model was developed and applied to thermal radiation calculated for a worst-case scenario of the ANZAC frigate's air weapons magazine. Calculated results showed that water droplets in the form of mists and fogs were more effective in blocking thermal radiation than larger water droplets in the form of spray or rain. The convective component of heat transfer is also identified as being important and follow-on work is required to determine its magnitude.

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The Effect of Water Mist and Water Spray on Radiative Heat Transfer for Stored Ordnance

Executive Summary

Water sprays and mists are a common method of suppressing fires within compartments and magazines and extensive studies have been performed to determine their extinguishing capabilities. However, limited information is available on the ability of water sprays and mists to mitigate thermal radiation. Such a situation may occur when there is a fire in a compartment adjacent to a weapons magazine. This technical note describes a technique for assessing the attenuating effects of water sprays and mists on thermal radiation in such a situation. The method applies Mie theory and an analytical technique to calculate the transmissivity of water sprays. Results show that, for a given water droplet mass loading, smaller water droplets have a much higher attenuating effect than larger droplets. The water droplet radiation attenuation model was also embedded into a combustion and heat transfer code developed previously for ordnance heat transfer studies. Quantitative results for a worst-case scenario on the ANZAC air weapons magazine are presented and indicate the reduction in radiative heat transfer to ordnance cylinders for various water droplet sizes and mass loadings. Convective heat transfer is not considered in this study and it is suggested that follow-on work be performed to assess this contribution to the heat transfer to ordnance.

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Dr Con Doolan graduated from the University of Queensland in 1992 with a Bachelor of Mechanical Engineering. He later conducted research on hypervelocity wind tunnels and was awarded a Doctor of Philosophy in 1997. Dr Doolan joined DSTO in 2000 after working at the University of Glasgow on helicopter aerodynamics. He now performs research on missile propulsion systems for the ADF and has interests in modelling shock ignition, cookoff response and advanced propulsion systems.

Contents

1. Introduction

Exposure of ordnance to heat over a period of time can result in a phenomenon known as `cookoff', which may be defined as the reaction of a weapon system (i.e. detonation, explosion, deflagration, etc) to an unplanned source of heat, such as a fire or thermal radiation. Cookoff is a major concern to Naval forces as it directly affects the safety of personnel, the survivability of platforms and also influences operations. Recently, (Doolan, 2001) efforts have been made to determine the heat transfer to munitions stored in a magazine when there is a fire in an adjacent compartment in order to define boundary conditions for cookoff modelling studies. This technical note is an extension of this work to determine the effect of water mist and water spray on the radiative heat transfer to stored ordnance. A thermal radiation mitigation model is developed for water droplets using Mie theory and a complex refractive index for water. This theory is then applied to the ANZAC air weapons magazine to determine the effect on heat transfer to ordnance when there is a fire in an adjacent compartment.

There have been numerous studies on using water spray or water mist for the suppression of fire (e.g. Bill et al. (1998), Burch et al. (2001)). There are relatively fewer studies however, on the ability of water spray and mist to mitigate thermal radiation. Demble et al. (1997) provide a method of determining the radiation mitigation properties of water spray curtains. This study uses Mie theory to derive a computational model that was validated against experiments with reasonable success. Ravigururajan and Beltran (1989) provide an analytical method of determining an attenuation model for thermal radiation through water droplets. The method outlined below uses a combination of computational and analytical methods to determine the overall heat transfer to munitions.

2. Mie Scattering Model for Water Droplets

It is assumed that water exists in the liquid phase only and is evenly distributed throughout the air phase and scatters radiation. No allowance is made for scattering or absorption by water vapour or solid suspended particles. While these phenomena exist, it was decided to limit the model to a pure liquid water and air gas phase to give conservative estimates of the heat transfer to stored ordnance without increasing the complexity of the model more than it needed to be.

Water droplets in air have the interesting ability to simultaneously scatter and absorb radiation incident upon it. Mie theory (Van De Hulst, 1957) provides the means to determine the extinction of radiation incident upon a water droplet. The two important independent variables in Mie theory are the size parameter (x):

$$x = \frac{2\pi r}{\lambda} \qquad (1)$$

and

$$z = mx \tag{2}$$

where r is the radius of the water droplet, λ is the wavelength of the incident radiation and m is the complex refractive index of the water droplet:

$$m = n_1 + ik \tag{3}$$

where n_1 is the real component (the refractive factor of the index) and k is the imaginary component (absorption factor of the index). The absorption factor (k) is related to the absorption coefficient (a) by the relation:

$$k = \frac{a\lambda}{4\pi} \tag{4}$$

The Extinction Efficiency Factor (Q_{ext}) and the Scattering Efficiency Factor (Q_{sca}) are defined as:

$$Q_{ext} = \frac{2}{x^2} \sum_{n=1}^{N} (2n+1) \operatorname{Re}(a_n + b_n) \tag{5}$$

$$Q_{Sca} = \frac{2}{x^2} \sum_{n=1}^{N} (2n+1)\left(\left|a_n\right|^2 + \left|b_n\right|^2\right) \tag{6}$$

where N is number of terms in the summation (Wiscombe, 1980), a_n and b_n are the Mie Coefficients:

$$a_n = \frac{\left\{\dfrac{A_n(z)}{m} + \dfrac{n}{x}\right\} \psi_n(x) - \psi_{n-1}(x)}{\left\{\dfrac{A_n(z)}{m} + \dfrac{n}{x}\right\} \zeta_n(x) - \zeta_{n-1}(x)} \tag{7}$$

$$b_n = \frac{\left\{m A_n(z) + \dfrac{n}{x}\right\} \psi_n(x) - \psi_{n-1}(x)}{\left\{m A_n(z) + \dfrac{n}{x}\right\} \zeta_n(x) - \zeta_{n-1}(x)} \tag{8}$$

Here, ψ_n and ζ_n are the Riccati-Bessel functions and $A_n(z)$ is the logarithmic derivative, which are determined from recurrence relations. In this work, the Mie scattering algorithms of Wiscombe (1980) are used to determine all the Mie theory variables to determine the extinction coefficient using an efficient recurrence scheme.

The data of Segelstein (1981) are used for the complex index of refraction for water. Figure 1 illustrates the variation of n_1 and k with incident radiation wavelength. The wavelength range available in the Segelstein data is much larger than is required for the thermal radiation study presented in this report. However, the full data set is displayed in Fig. 1 for completeness.

Using the theory of Ravigururajan and Beltran (1989), the extinction efficiency factor can be used to determine a monochromatic transmissivity (τ_λ):

$$\tau_\lambda = \exp\left(-\frac{3Q_{ext}WL}{4r\rho}\right) \tag{9}$$

where ρ is the density of the water, L is the distance the radiation is to pass and W is the droplet mass loading (or concentration):

$$W = \rho\frac{4}{3}\pi r^3 N_d \tag{10}$$

where N_d is the number of drops per unit volume.
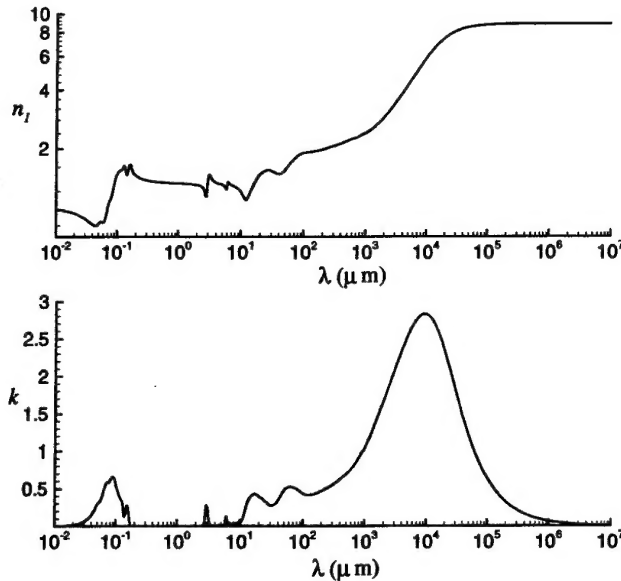

Figure 1. Complex refractive index data for water (Segelstein, 1981).

Hence, radiation transmitted between two surfaces (surface 1 to surface 2) is,

$$Q_{1 \to 2} = \varepsilon \int_0^\infty I_\lambda \tau_\lambda F_{1 \to 2} d\lambda \qquad (11)$$

where Q is the radiation transmitted, ε is the emissivity of surface 1 and F is the relevant shape factor between the surfaces. The monochromatic radiation intensity (I_λ) is (Holman, 1981),

$$I_\lambda = \frac{C_1 \lambda^{-5}}{e^{-C_2/\lambda T} - 1} \qquad (12)$$

where C_1 is a constant (3.743×10^8) , C_2 is a constant (1.4387×10^4) and T is the temperature in Kelvin.

The radiation model described here has been placed into a combustion and heat transfer code designed to calculate the heat transfer distribution around ordnance stored in steel magazines when there is a fire in an adjacent room or compartment (Doolan, 2001). The shape factors for Eq. (11) are calculated in this code and are documented in Doolan (2001).

3. Results

3.1 Water Droplet Characteristics

Four water droplet diameters are investigated in this study. They are described in Table 1 and correspond to a fog, mist, spray and rain. Determining the appropriate mass concentration (W) can be difficult and is usually done empirically for many spray systems. For the calculations presented here, W is varied from 0.01 to 0.7 kg/m^3 in order to cover the full range of droplet loadings possible. The upper limit of 0.7 kg/m^3 was determined from Darwin and Williams (1999) who suggest that this value is required to suppress fuel/air explosions.

Table 1. Droplet Radii used in this study.

Droplet radius (µm)	Description
10	Fog
50	Mist
100	Spray
500	Rain

Figure 2 shows the calculated extinction and absorption efficiencies for the four water droplet sizes shown in Table 1. The absorption efficiency (Q_{abs}) is the difference between the extinction (or total) efficiency and the scattering efficiency:

$$Q_{abs} = Q_{ext} - Q_{sca} \tag{13}$$

The results in Fig. 2 show that the extinction efficiency varies considerably with wavelength for the 10 µm case. As the water droplet increases in size, the magnitude of this variation diminishes. The results also indicate that absorption plays a significant role over most of the spectrum, except for a noticeable region in the 0.2-5 µm wavelength region where scattering dominates the extinction mechanism. This region of the spectrum is important for thermal radiation and illustrates the importance of calculating the Mie scattering coefficients correctly.
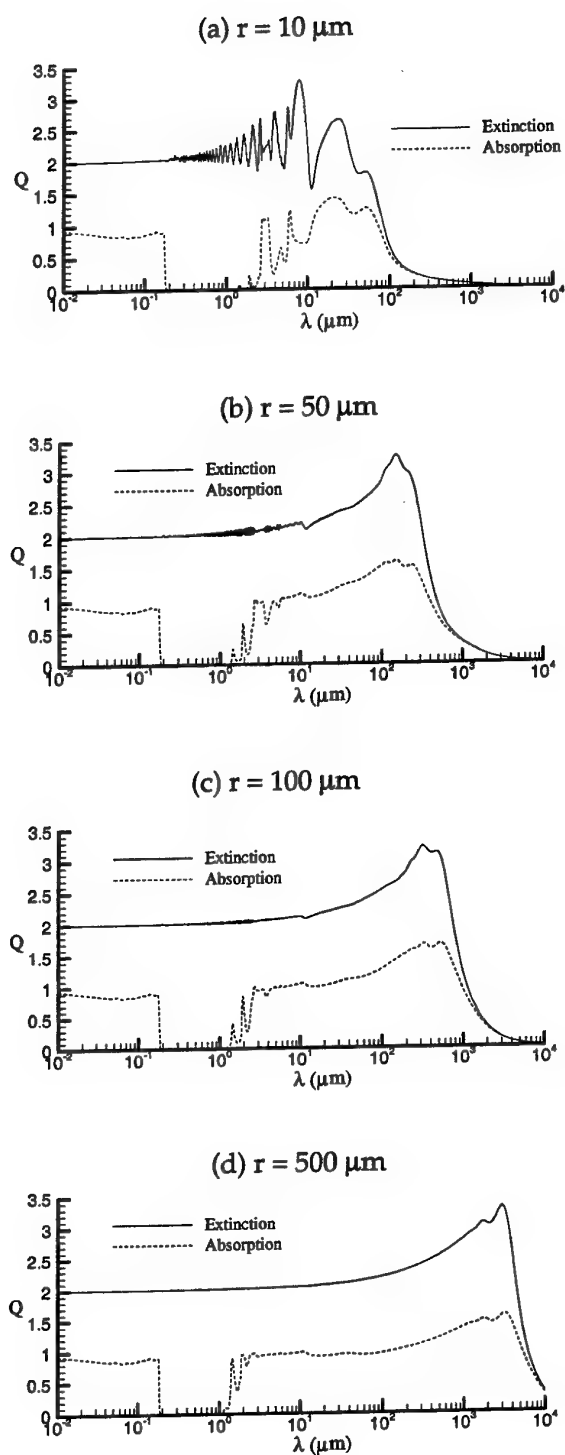
Figure 2. Extinction and absorption efficiencies for water droplets with various radii.
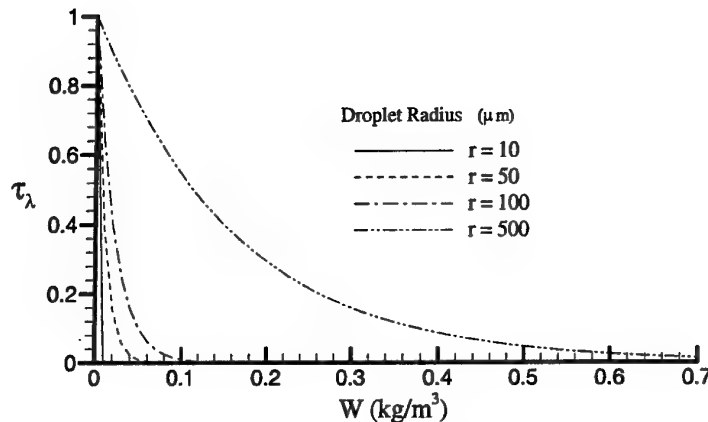
Figure 3. Transmissivity results for water droplets of different sizes and $\lambda = 3 \mu m$.

Figure 3 illustrates the effect of water droplet loading (W) on the transmissivity of radiation with an incident wavelength of 3 μm. This wavelength was chosen because it is within the spectral region representative of thermal radiation. Water droplets with small radius have a dramatic effect on reducing the transmitted radiation, with $r = 10$ μm almost completely blocking the radiation over the droplet loadings considered in this study. As the droplet radius increases, the medium allows more incident radiation through for the same droplet loading. At $r = 500$ μm, the droplet loading needs to be above 0.7 kg/m³ to be completely effective at blocking the incident radiation. Similar results to Fig. 3 were calculated by Ravigururajan and Beltran (1989) who used the approximate Mie correlations of Dermendjian et al. (1961).

Some care should be observed when choosing a water droplet loading for performing calculations. The droplet loading is a strong function of the droplet radius. For example, the maximum droplet loading of 0.7 kg/m³ can only be obtained for very fine water mists or fogs and therefore does not apply to the spray (100 μm) or rain (500 μm) cases. Typical maximum droplet loadings for these systems vary from between 0.1 and 0.2 kg/m³. As the fine fog and mist sprays are completely effective above 0.1 kg/m³, there seems little reason for performing heat transfer calculations above a droplet loading of 0.2 kg/m³ for the four droplet sizes considered here. Therefore the calculations presented in the next section will concentrate on a droplet loading range of 0.01 to 0.2 kg/m³.

3.2 Ordnance Heat Transfer Calculations

The water droplet radiation model described in Section 2 was embedded into a combustion and heat transfer code (Doolan, 2001). This code is used to determine the radiative heat transfer to ordnance cylinders (representing missiles and ammunition) stored in steel magazines when there is a fire in an adjacent compartment. Figure 4 illustrates the geometry used to model the ordnance heating. The code determines the heat release of a fire in an adjacent compartment (the fire compartment) that heats the

common bulkhead separating the fire and the magazine. Additional compartments are modelled (subject to the ship or facility architecture) to determine the heat losses from the system.
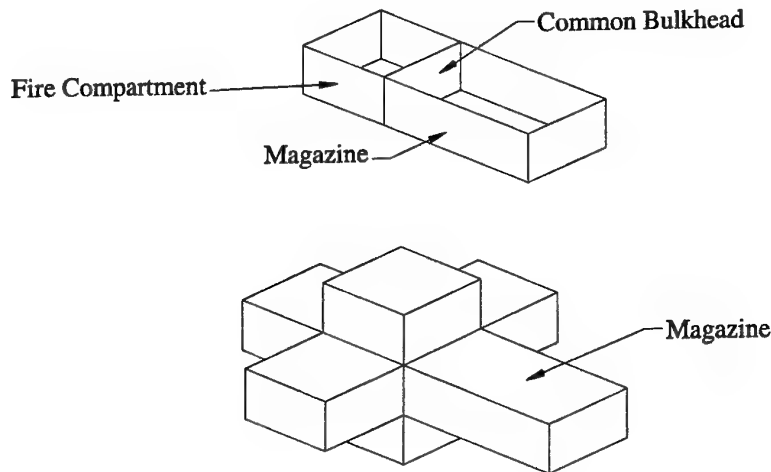

Figure 4. Schematic of compartment layout used for heating calculations.

Ordnance stored within the magazine is represented as a cylinder. Radiative heat transfer from the common bulkhead to the ordnance cylinder is calculated using an iterative method detailed in Doolan (2001) and is summarised here. Figure 5 illustrates the computational geometry used in the model. The common bulkhead is discretised into 2500 equal elemental areas. The net thermal radiation between any two elements dA_1 and dA_2 can be calculated using the following relation (Holman 1981),

$$dq_{1\rightarrow2} = \varepsilon_w \sigma (T_W^4 - T_s^4)\cos\phi_1 \cos\phi_2 \frac{dA_1 dA_2}{\pi r^2} \qquad (14)$$

where T_W is the common bulkhead temperature, ε_w is the emissivity of the common bulkhead, T_s is the surface temperature of the ordnance at dA_2 and the other symbols are defined in Fig. 5. The angles, ϕ_1 and ϕ_2, are measured relative to the normal from each respective surface. The heat transfer per unit area at a point on the ordnance cylinder due to the radiation from dA_1 can be determined by dividing both sides of Eq. 14 by dA_2. To calculate the total heating rate at a point on the ordnance cylinder it is necessary to sum the components from each element on the bulkhead (or integrate in the limit $dA_1 \rightarrow 0$). This can be done for any point on the ordnance cylinder and is calculated in the numerical model at 200 locations around the circumference of a section through the ordnance cylinder.
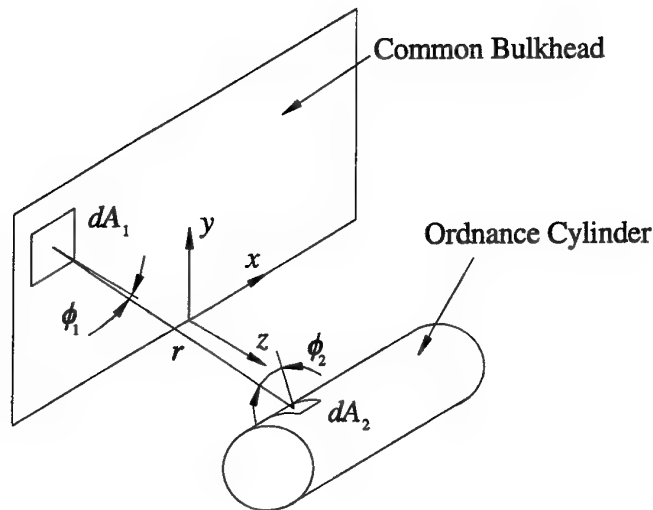
Figure 5. Computational geometry used to determine azimuthal radiative heat transfer from the heated common bulkhead and the ordnance cylinder.

Doolan (2001) performed heat transfer simulations for the ANZAC air weapons magazine and an ordnance cylinder representing the Penguin anti-ship missile. It was found that the highest heating load occurred when the missile was placed in a weapons trolley 0.49 m from the deck and 1.04 m from the heated bulkhead (these dimensions represent the closest point the missile can be to a heated bulkhead when transported in a weapons trolley). Figure 6 shows the heat transfer results obtained from that study. In Fig. 6, the x-axis represents the azimuth around the ordnance cylinder where 0 degrees is the point on the surface of the cylinder facing the heated bulkhead and 90 degrees is perpendicular to this point and is on the top surface of the cylinder.
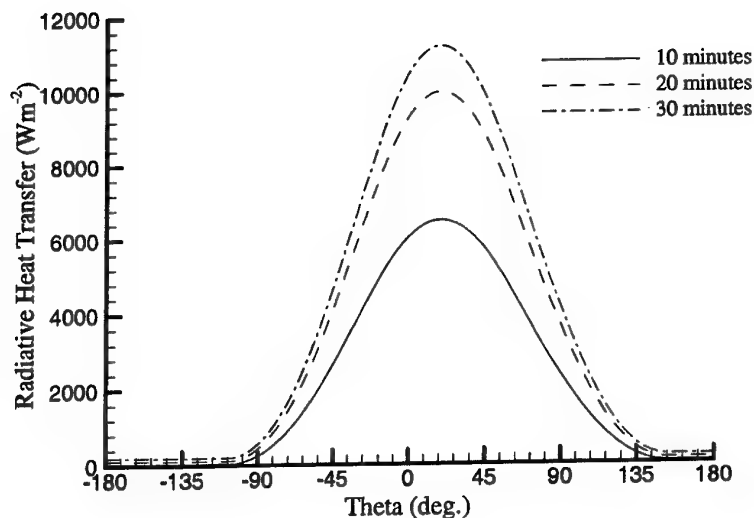
Figure 6. Radiative heat transfer to an ordnance cylinder (representing the Penguin ASM) for worst-case situation (weapons trolley) in ANZAC air weapons magazine, from Doolan (2001).

The results in Fig. 6 include a radiative component from the gas contained within the magazine. As discussed in Doolan (2001), soot from decomposing plastics or from the fire compartment was assumed to contribute to the heat transfer through radiation in the suspended phase. The calculations presented below for water mists and sprays set this component to zero as the spray system is assumed to be an efficient scrubbing mechanism able to remove soot particles from the air.

Radiative heat transfer calculations were performed for the worst-case situation identical to that used for the results in Fig. 6 except that a fire mitigation system was simulated by dispersing water droplets of uniform diameter throughout the magazine space. The four droplet sizes in Table 1 were used along with a range of droplet loadings. Figure 7 summarises the results of this analysis. Here, the vertical axis represents the peak radiative heating rate after 30 minutes of heating (Q_2) divided by the peak radiative heating rate at 30 minutes from the original calculation with no spray system (Q_o, from Fig. 6).

The smaller water droplets provide the most effective thermal radiation mitigation while the large 500 μm droplets are the least effective.
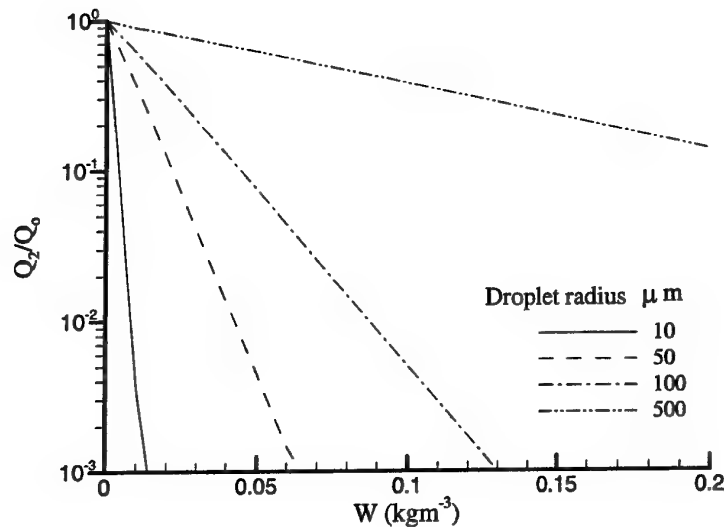
Figure 7. Ratio of peak radiative heating rate (at t = 30 min) with water droplet mitigation to peak radiative heating rate with no water droplet mitigation (at t = 30 min).

3.3 Convective Heat Transfer

Results presented in this technical note describe the effects of water sprays on thermal radiative heat transfer only. It can be argued that, when spray systems are employed, convective heat transfer may play a significant role in the heat transfer to ordnance. Schmidt and Boye (2001) have published some convective heat transfer coefficient data for heated cylinders cooled by water sprays. While not directly applicable to the application of ordnance cylinders, it suggests that the effects of convection can be significant and are independent of droplet size. In order to resolve this issue for the present application, a research project has been initiated with the University of Adelaide. The aim of this study is to experimentally observe the thermal mitigation effects of water sprays and mists and to obtain estimates of the radiative and convective cooling characteristics of these sprays.

4. Summary

A method, based on Mie theory, has been developed for assessing the mitigating effects of water droplets on thermal radiation. It has been applied to ordnance cylinders, representing missiles in a magazine, when there is a fire in a compartment adjacent to the magazine. Results show that small droplet radii provide a better capability in attenuating thermal radiation than large droplets due their ability to scatter radiation more efficiently. The model was also embedded into a combustion and heat transfer code (Doolan, 2001) and used to estimate the reduction in thermal radiation to ordnance cylinders for a worst case scenario of the ANZAC air weapons magazine. For the same droplet mass loading per unit volume, water mists provide

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much better thermal mitigation properties compared with water spray or rain. These results do not take into account convective heat transfer, which according the available literature may be significant. Therefore future work in this area should involve the measurement of both radiative and convective heat transfer components for objects immersed in water sprays that are subjected to thermal radiation.

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